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BELLCOMM INC.

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SMALL-SCALE LUNAR TOPOGRAPHY

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Bellcomm, Inc.
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Abstract

The evidence bearing on the determination of lunar small-scale topography is critically examined. It is shown that neither the concept of a largely smooth lunar surface (in the centimeter-meter size range) nor the concept of a largely rough lunar surface (in the same size range) is demonstrably correct. However, since at least as good an argument can be made for a rough moon as for a smooth moon, it is urged that the smooth moon concept be dropped in favor of a more conservative model for design purposes.

SMALL-SCALE LUNAR TOPOGRAPHY

1.0 INTRODUCTION

Possibly the most significant aspect of the lunar environment, for manned and unmanned landings, is the small-scale surface relief which may be encountered in the touchdown area. It would, therefore, be very desirable to be able to predict the nature and distribution of marial small-scale relief on the basis of our present information. In fact, such predictions have been and continue to be "confidently" made. It is the purpose of this paper to evaluate the data and assumptions upon which these predictions are based.

2.0 ARGUMENTS FOR A SMOOTH MOON

There are two approaches to the conclusion that the lunar surface is essentially smooth (i.e. contains only a small percentage of pits, protuberances, etc. in the centimeter to meter size range). First, the prevalent interpretation of the radar data indicates that the moon behaves more or less as a smooth sphere for radar wavelengths down to 3 cm. Given this interpretation, it is possible to evoke a number of reasonable processes which would result in such a configuration. Conversely, it has been argued that a consideration of our present knowledge of lunar processes, the lengths of time during which these processes have operated, and their effective operational rates, leads to the inevitable conclusion that at least the lunar maria are smooth, in the sense defined above. The radar data, then, merely substantiates this independent conclusion.

2.1 Radar Data

It is beyond the scope of this report to discuss the pros and cons of the radar argument in any detail. Suffice it to say there is still considerable doubt connected with the interpretation of radar returns, because of the necessary simplifications and assumptions which must be made and the almost complete lack of any empirical substantiation. It would, in fact, appear that the theoretical nature of the radar calculations and the ambiguities present in the work to date make it unwise to base the argument for a smooth lunar surface solely on the radar data at this time.*

2.2 Processes Argument for a Smooth Moon

It is possible to argue that the formation of the lunar maria resulted in a more or less uniform surface which displayed few irregularities of any size and that subsequent processes have introduced little if any

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* For an analysis of radar data and its possible interpretations, see the accompanying Bellcomm report by W.B. Thompson entitled "Lunar Radar Studies."

additional roughness. But this is a rather naive argument, for it assumes (among other things) an origin which gives rise to uniformly smooth surfaces and a knowledge of said origin. The former is unlikely and the latter is not true.

A more compelling argument, superficially, runs as follows: The lunar maria are very old, probably 4.5×10^9 years old. During this time, the primary agent of surface modification has been meteoritic infall. The meteoritic infall is heavily dominated by small particles, so that the net effect of this bombardment will be to smooth out the marial surface by cutting down the topographic highs and filling in the topographic lows with eroded material. The actual accretion of fine meteoric material may also help smooth the surface. Now, if we calculate the rate of erosion of an unprotected body in space from the observed meteoritic flux in the vicinity of the earth-moon system, we find that the marial surfaces must have experienced enough erosion over 4.5×10^9 years to remove a layer of material tens of meters thick. Since any reasonable process which we can visualize for marial formation could not have produced much small-scale relief greater than 10-20 meters (at the outside), any original roughness has by this time been almost completely eradicated.

In the following discussion, each major point of the above argument is isolated, explicitly stated, and critically examined.

The maria are 4.5×10^9 years old.

A reasonably representative cross-section of estimates of marial ages shows the following spread:

Kuiper (2) - Estimates the maria are 4.5×10^9 years old. His evidence is "based on the dating of meteorites and the earth itself in a series of papers well known to geophysicists ... The conclusion that the asteroids were partly molten and solidified about 4.5×10^9 years ago is based on much geochemical and astronomical evidence." However, even assuming that the ages assigned to meteorites, asteroids and the earth itself are correct, there is no necessary connection between these events and marial formation.

Urey (3) - Believes that the maria were all formed in a very short period of time, early in the history of the solar system (presumably $\sim 4 \times 10^9$ years ago). He bases this belief on the supposition that "The moon was captured by the Earth early in the history of the solar system ... Shortly after its capture by the Earth it was intensively bombarded for a short period of time. The objects which fell on the moon at that time were satellites of the Earth and fell with moderate velocities." This bombardment led to the formation of most of the lunar surface features visible today, including the maria.

Fielder (4) - Says the continents are six times older than the maria. His evidence is a vague reference to crater counting (most authorities agree that the age of the moon as a planetary body is 4-5 x 10^9 years, so if continents were formed very early, Fielder would claim the maria were formed somewhat less than 10^9 years ago).

Khabakov (5) - Estimates the maria are very young -- on the order of tens of millions of years old. His estimate is based on deriving the entire history of the moon, mainly by well-known geologic methods such as the principle of superposition. In this relative sequence, marial formation is only followed by the most recent period in the lunar history. Thus by estimating the length of time that the most recent period encompasses, he can estimate the termination of the period of marial development.

Shoemaker (personal communication) - Estimates the maria are 4.5 x 10^9 years old. His estimate is based on determining the infall rate for larger craters (> 1 Km) on the lunar maria, largely by extrapolating from Brown's determination (6) of the flux of smaller meteorites (from observed terrestrial falls), and multiplying by an appropriate factor to compensate for the lesser lunar gravity (which depends on the assumed meteorite velocity). He then counts marial craters and assuming a relatively constant infall rate over the last 4×10^9 years, he can calculate the age from his previously determined infall rate.

Öpik (7) - Estimates the maria are 4.5×10^9 years old. This estimate is based on marial crater counts and an infall rate derived in a manner similar to that attributed to Shoemaker in the preceding paragraph.

Baldwin (8) - Suggests "... the lava flows (of the maria) may be hundreds of millions of years, or even billions of years younger than the earliest observable surface markings." This suggestion is based on the assumption of a continuous decline in the rate of infall to the moon ..."and is in better agreement with reasonable thermal histories of the moon such as have been developed by MacDonald..."

The estimate of 4.5×10^9 years for marial ages necessitates a very high meteorite flux before marial formation, an abrupt drop in this flux immediately before or during marial formation and a much lower, approximately constant flux from marial formation to the present time. Baldwin's assumption of "a continuous decline in rate of infall to the moon" leads to a younger age for the maria. To complete the sequence, it should also be pointed out that if the meteorite flux has been approximately constant since the first impacts on the moon, then the maria must be only 1/30 as old as the continents (since for every crater of a given size on the maria there are 30 craters of the same size on the continents, reference 9). This leads to an estimate of $1\text{-}2 \times 10^8$ years for the age of the maria. Of course, all the estimated ages based on crater counts might have to be revised downward if a substantial percentage of lunar craters were found to be volcanic rather than meteoritic in origin.

To summarize then, there does not seem to be any compelling reason for believing the maria are 4.5×10^9 years old. What evidence exists is far from conclusive and the postulated ages are little more than personal opinions. Under these circumstances, it is rather surprising that 4.5×10^9 years does seem to be the favorite estimate. Sentiment aside, however, the available data easily lends itself to estimates of marial ages which encompass a spread of a factor of 30 or more (from the upper limit of 4.5×10^9), as can be seen from the other divergent estimates.

<u>The moon has been almost a "dead world" for the last 4.5×10^9 years, so that the only events significantly modifying the surface have been meteoritic in nature</u>.

Recent thermal calculations (10) indicate that the moon must be hot enough to promote igneous activity at moderate depths, unless it is almost totally devoid of radioactive elements or these elements are distributed in a very peculiar way. This is not consistent with a "dead world" concept. In fact, there is considerable photographic evidence of crustal fracturing, tilting, slumping, and at least partial isostatic adjustment, not to mention the probable, past production of copious amounts of molten material which now cover the maria.

<u>Erosion rates calculated from meteorite data: 1) are reasonably accurate; 2) lead to substantial erosion over long periods of time; and 3) are applicable to the moon.</u>

The estimates tabulated below probably define the upper and lower limits calculated by <u>responsible</u> scientists.

Whipple (11) - Calculated an erosion rate for stony meteorites of <u>170 Å/year (75 meters/4.5 x 10^9 years</u>). The calculation is based on the amounts of radiation-produced ^{38}A and ^{39}A in a number of stony meteorites. Whipple considers the calculation accurate to a factor of 2, but cautions that because of a necessary simplification, the calculation gives the maximum possible erosion rate. The actual rate may be considerable smaller. Similar calculations, using ^{21}Ne, by Fisher (12) are lower by a factor of 10.

Öpik (7) - Estimates "... a dust layer of the order of 20 meters could have been battered out of an exposed rock surface during the lifetime of the moon (assumed to be 4.5×10^9 years)." The estimate is based on "... the content of micrometeoritic material in interplanetary space ..." and an erosion rate appropriate to a velocity of impacting particles of 5 KM/sec. No estimated error is given.

Orrok (personal communication) - Calculates an erosion rate of 10 Å/year (4.5 meters/4.5×10^9 years) for aluminum metal in space. The calculation is based on the latest meteorite flux data available but is considered to be no more accurate than plus or minus an order of magnitude. To be strictly comparable to the Whipple and Öpik estimates (both of which are for silicate material), Orrok's estimate should be raised somewhat.

It should be apparent that there are substantial limits of error involved in calculations of this sort. Orrok's range of equally probable values, for example, is 0.45 to 45.0 meters/4.5×10^9 years. However, even more important than this is the fact that none of the above values may be applicable to the lunar surface, for each is based on the assumption that the eroded material is immediately removed from the attacked surface and consequently cannot impede subsequent erosion. In the case of the moon, there is good reason for believing the impact-produced dust may have adhesive properties, so that a thin dust layer could cling to even the steepest slopes. This would provide an effective buffer against micrometeoritic erosion, perhaps reducing the erosion rate, as compared to a continuously bare surface, by as much as two orders of magnitude. This concept has been recognized and elucidated by a number of people. Öpik (13), for example, after calculating an unhindered erosion rate of 20 meters/4.5 x 10^9 years and then considering the effect of a thin ubiquitous dust layer, concludes "... such depth actually cannot be attained and the erosion will remain purely superficial ... The total mass of eroded dust will be small, not more than an equivalent layer of <u>20-100 cm</u>." Therefore, even if the upper limit of calculated erosion for bare rock is correct, the actual erosion on the lunar surface may remain negligible.

<u>The accretion of fine meteoric material may also help smooth out the marial topography</u>.

The accumulation of meteoritic dust over 4.5 x 10^9 years could amount to a uniform layer over the whole lunar surface, 20-40 cm thick, if there were no other considerations. In fact, a small fraction of the material ejected by the cratering process will escape from the lunar gravitational field. But there is some evidence (14) that the escaping mass may be greater than the mass of the incident particle. Thus, disregarding the necessary assumption that the maria are very old, the available evidence indicates that there is probably no net accretion due to micrometeoritic infall.

The rate of impact of larger meteoritic objects is so small that the number of craters produced over 4.5×10^9 years per unit area of selected marial regions is not appreciable.

If the empirically determined curve representing cumulative frequency versus size distribution of marial craters is extrapolated to the size range 1-100 meters, the resulting crater density is essentially negligible (Figure 1).* But there is no good reason for believing such a log-log plot remains linear over an extrapolation of three orders of magnitude. In fact, plotting the "fireballs" and observed meteorite falls on the same graph indicates a non-linear trend, so that it may be wiser to interpolate rather than extrapolate. In this case, if one is interested in 0.5 meter craters, for example, it turns out that a mean density of one 0.5 meter or larger crater every two square meters is predicted for marial surfaces if the maria are 4.5×10^9 years old. This is not an insignificant number. It could be a factor of 10 higher (estimated error).

* For a complete discussion of the derivation of the curves shown in Figure 1, see the accompanying Bellcomm report by G.T. Orrok entitled "Meteoric Infall and Lunar Surface Roughness."

The interpolated frequency is based on terrestrial infall data, so it should be reduced by a factor commensurate with the lesser gravitational attraction of the moon (lunar impact frequency being roughly 0.5 - 0.9 times terrestrial frequency, depending upon the assumed meteorite velocity, reference 15). However, this reduction is at least balanced by the facts that the introduced surface roughness is not confined to the area defined by the crater diameter and the predicted frequency is only for primary impacts (thus secondary impacts will increase this figure somewhat).

It has been argued that increasing the primary flux does not increase the number of meter-sized craters on the lunar surface, because the flux of smaller meteorites will also increase and since the population is heavily dominated by the micrometeoritic sizes, the increased erosion will more than compensate for the increase of meter-sized craters by cutting most of them down to the surrounding level. Again, this argument is only valid if the surface being eroded is continually exposed. If, in fact, the surface is buffered (even on steep slopes) by a layer of previously formed ejecta, then it can be shown that the erosion is dominated by the size-class of meteorites which is just numerous enough to completely cover the surface with craters. For the crater distribution shown in Figure 1, craters larger than 0.5 meters are not significantly eroded by that part of the flux which is the dominant eroding force (forming 0.1 m craters).*

Returning briefly to the question of the age of the maria, note that the fit between marial cratering flux, "fireballs", and observed falls is rather insensitive to changes in the assumed age of the maria. (In Figure 1, the dot-dash line is based on an assumed age of 2×10^9 years; the solid line is based on an assumed age of 4.5×10^9 years).

The foregoing analysis demonstrates that none of the assumptions implicit in the "processes" argument for a smooth moon exhibit much validity. Clearly then, it must be impossible to conclude that the surface roughness of selected marial regions is negligible, without additional evidence.

3.0 THE ARGUMENT FOR ROUGH MARIA

If the prevalent interpretation of the radar data is disregarded, it is possible to argue for the probability of dominantly rough terrain in marial regions. Such an argument would run as follows: Throughout the history of

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* For a complete discussion of the relation between that cratering which contributes to surface roughness and that cratering which tends to remove surface roughness, see the accompanying Bellcomm report by G.T. Orrok entitled "Meteoric Infall and Lunar Surface Roughness."

lunar observation, improved instrumentation has always revealed a multitude of smaller and smaller-scale details on what had previously appeared to be featureless areas. It has been possible for some time to just discern details with the telescope-eye combination, having minimum dimensions on the order of 300-500 feet. Experienced observers of the lunar surface are generally impressed with the density of these features, even on lunar maria. There is no good reason to expect a sharp cut-off for these surface features, such that below a certain size, their number is greatly diminished. In fact, all our observational data to date tells us that as the size decreases, the number of such features should increase markedly. We should, therefore, expect a considerable density of topographic features having dimensions such that the surface is extremely hazardous for landing a manned vehicle.

A consideration of the processes involved in the formation and modification of lunar maria leads, similarly, to a picture of substantial small-scale surface roughness. There are good reasons for believing the maria represent vast lava fields, presently covered by a thin layer of dust. Although the occurrence, on the earth, of reasonably smooth lava field surfaces is not uncommon, the lack of an atmosphere is conducive to the dominance of the rough surface type of flow on the moon. This is so because the upper portions of the molten material would be much more violently degassed in the high vacuum lunar environment than in an otherwise comparable terrestrial environment. The violent degassing not only results in a rough, jagged surface texture, but in the upper portion of the flow solidifying to a frothy, incompetent material which may be easily broken and piled up haphazardly by the still flowing material underneath.

It is not possible to determine the age of the marial rocks at present, but even if they were 4.5×10^9 years old, the smoothing effect of micrometeorite bombardment over this period has been shown to be negligible. On the other hand, interpolation of available data bearing on the flux of larger meteoritic objects indicates that, over this period of time, a minimum of 25% of the surface has been pockmarked by craters ≥ 0.5 meters in diameter and covered with throw-out from the cratering process. Thus the processes of formation and subsequent modification have resulted in substantial small-scale roughness over a large portion - probably most - of the marial surfaces.

The foregoing argument is no more valid than the smooth moon argument was shown to be.

The assessment of features which are on the edge of discernment, with the telescope-eye combination, is a highly subjective matter. Furthermore, the subjectivity is most probably biased toward an overestimation of the density (and relative roughness) of these features. This is a well-known phenomena encountered by microscopists when attempting to estimate the percentages of small amounts of strikingly different material, which are set in matrices of more undistinguished material. In microscopy, this is circumvented by actually counting a statistically significant number of random points. Unfortunately this is not possible with the features under discussion here --- there is no possibility of even a semi-quantitative estimate of their density. Thus while it may be true that smaller features are more numerous than those seen, it does not necessarily follow that these unseen features will constitute an appreciable portion of the surface.

The argument based on formative processes, although vividly detailed, is as naive as the similar argument for a smooth moon in that it presupposes a knowledge of the marial origins. Further, even if the assumption that the maria are covered with lava flows is granted, the additional assumption that such flows have rough surfaces is still unwarranted. The flow surface roughness is a function of the initial amount of contained gases (mainly

H_2O), the lava viscosity (which, in turn, depends on composition and temperature), the cooling rate of the molten material, the rapidity of the extrusion process (since a long, slow ascent to the surface would allow most of the volatile constituents to escape while the material remained molten), the actual rate of flow after extrusion, and the rate of change of flow after extrusion. It is extremely difficult to assess these variables for terrestrial lavas, much less lunar flows. For example, terrestrial volcanics commonly contain approximately 1 wt. % H_2O, which is close to the saturation value at liquidus temperatures and confining pressures of 1-2000 bars (and a not inconsiderable amount, by volume). But there is really no way of knowing whether this is primary magmatic water or whether it was picked up as the molten rock ascended through the water-rich, upper-crustal materials (which would most probably be absent on the moon).

The argument based on subsequent modifying processes is again subject to the same criticism leveled against the smooth moon argument. That is, to be valid, this argument must show that the best case which can be made for erosion and the worst case which can be made for increased roughness due to larger cratering events still results in the net (and preferably substantial) generation of small-scale roughness. In fact, the rough moon argument depends on the supposition that a buffer layer of previously ejected material blankets even the steepest slopes. Although this is not an unreasonable assumption, it is by no means a proven fact. If the rubble created by impacting objects remains unconsolidated, lunar slopes will be more or less continually exposed and the erosion by micrometeorites will dominate the moonscape. Finally, even if the buffer layer were present, the introduced roughness due to cratering may still be insignificant if the cratering flux is down by a factor of 10 (the estimated limit of error) or if the maria are much younger than 4.5×10^9 years old.

4.0 SUMMARY AND CONCLUSIONS

It cannot be demonstrated that either the smooth moon or the rough moon <u>concept</u> is wrong. It has been herein shown, however, that both the <u>argument</u> for a smooth surface and the <u>argument</u> for a rough surface are utterly incapable of rigidly demonstrating that either concept is right. Further, any argument for an intermediate surface suffers from the same shortcoming. This is so because of the uncertainties in the data on which they are based, the uncertainties in the data interpretation, and the unavoidable simplifications and assumptions necessary for the calculations (see, for example, the simplifications and assumptions in the accompanying Bellcomm report by G.T. Orrok). The answer that one gets is highly sensitive to these uncertainties and simplifications, i.e. order of magnitude estimates and calculations will not do, except to set upper and lower limits on what might actually be encountered.

Up to this point, no attempt has been made to assess the relative merits of the smooth surface and the rough surface arguments. It would be remiss, however, not to point out that at least as favorable a case can be made for a rough surface as for a smooth surface. Under these circumstances it would seem wise to be as conservative as is feasible in the design of vehicles for landing and operating on the lunar surface.

To circumvent such conservatism, it is appealing to postulate a heterogeneous surface, varying from very rough to very smooth. This, it is argued, eliminates the necessity of worrying about landing in rough areas. It is, however, replaced by the necessity of finding a suitably smooth area which is otherwise acceptable for landing. While there is no doubt that the lunar surface is heterogeneous with respect to small-scale topography, this fact alone is not sufficient information upon which to base design concepts. The admission of heterogeneity does not guarantee that significant parts of selected lunar areas are smooth, or, in fact, that any part of the lunar surface is acceptably smooth. Thus, unless it can be unequivocally shown that the search mode-hover stage combination can put a LEM down safely in an area or areas which may constitute only a small fraction of the entire marial surface, it would appear imperative to base design concepts on a lunar model characterized by substantial small-scale surface roughness.

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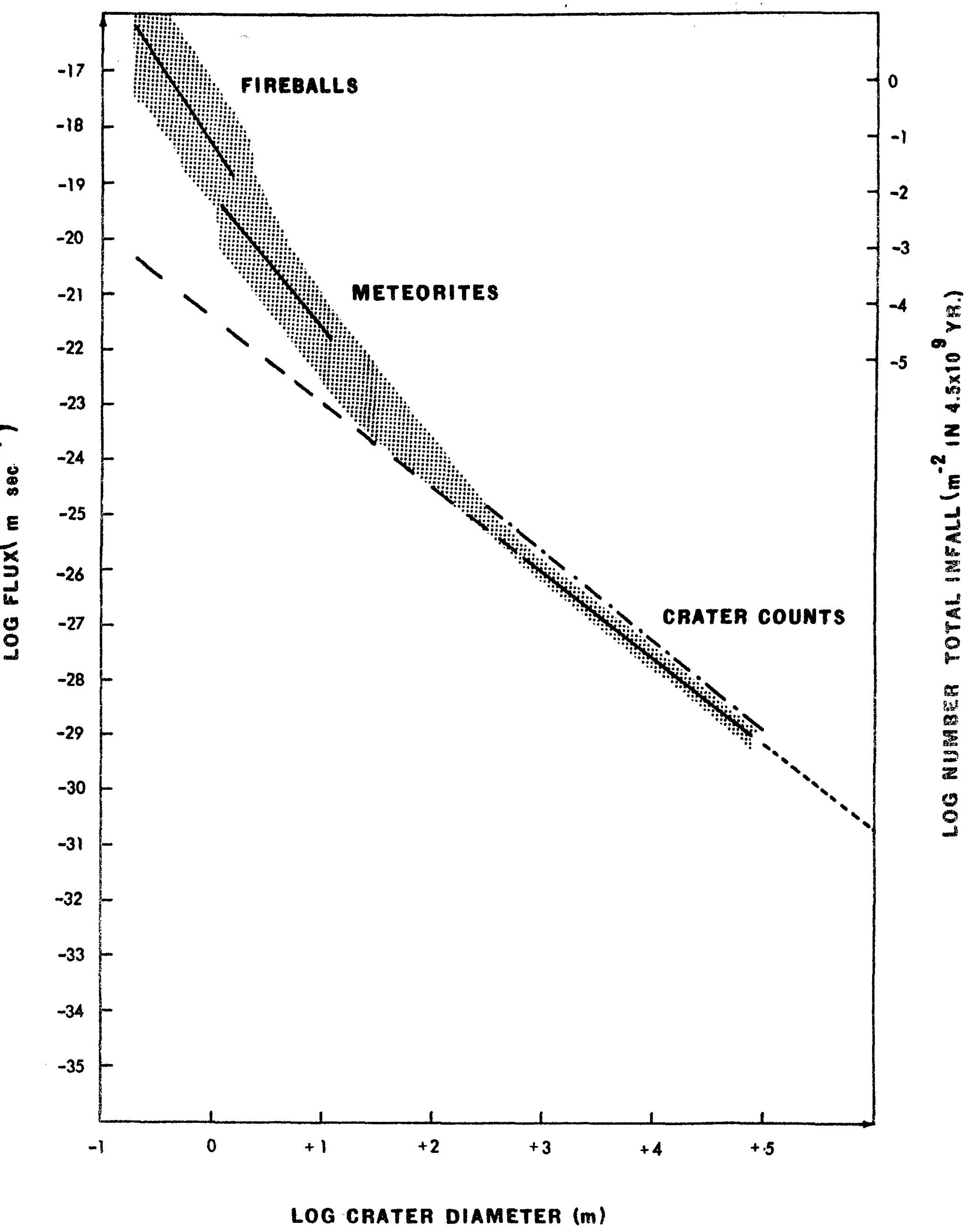

FIG.1 LOG CUMULATIVE FLUX OF HEAVY METEOROIDS AGAINST CRATER DIAMETER

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